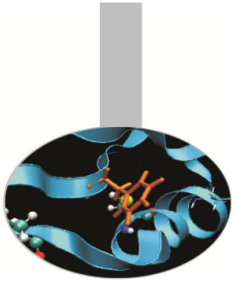
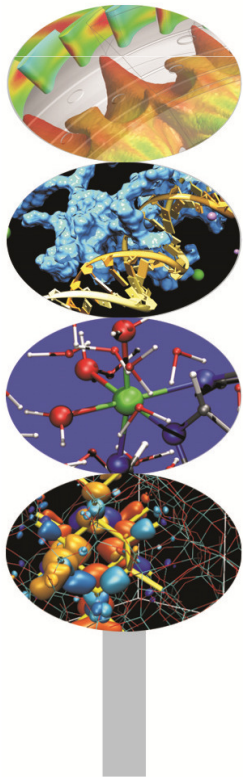
CINECA SCAI
SuperComputing Applications and Innovation



Profiling



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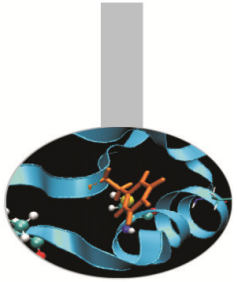
Introduction



A serial or parallel program is normally composed by a large number of procedures.

To optimize and parallelize a complex code is fundamental to find out the parts where most of time is spent.

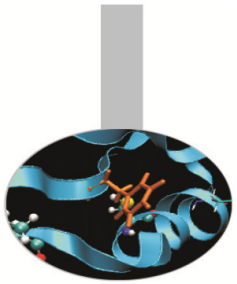
Moreover is very important to understand the graph of computation and the dependencies and correlations between the different sections of the code.

For a good scalability in **parallel programs**, it's necessary to have a good load and communication balancing between processes.

To **discover** the **hotspots** and the **bottlenecks** of a code and find out the **best optimization and parallelization strategy** the programmer can follow two common methods:

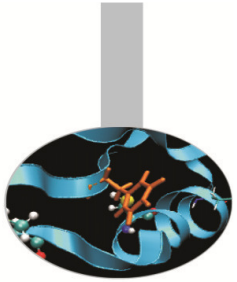
- Manual instumentation inserting timing and collecting functions (difficult)
- Automatic profiling using **profilers** (easier and very powerful)

Measuring execution time



- Both C/C++ and Fortran programmers are used to instrument the code with timing and printing functions to measure and collect or visualize the time spent in critical or computationally intensive code' sections.
  - **Fortran77**
    - `etime(),dtime()`
  - **Fortran90**
    - `cputime(), system_clock(), date_and_time()`
  - **C/C++**
    - `clock()`
- In this kind of operations it must be taken into account of:
  - Intrusivity
  - Granularity
  - Relaiability
  - Overhead
- **Very difficult task for third party complex codes**

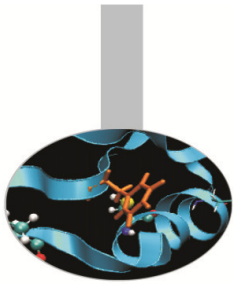
Measuring execution time



C example:

```
#include <time.h>
clock_t time1, time2;
double dub_time;
…
time1 = clock();
for (i = 0; i < nn; i++)
for (k = 0; k < nn; k++)
for (j = 0; j < nn; j ++)
c[i][j] = c[i][j] + a[i][k]*b[k][j];
time2 = clock();
dub_time = (time2 - time1)/(double) CLOCKS_PER_SEC;
printf("Time ----------------> %lf \n", dub_time);
```

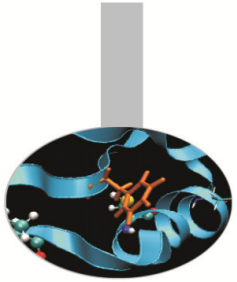
Measuring execution time



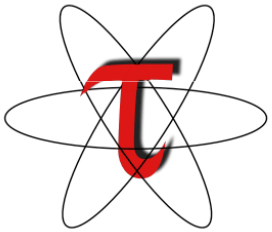
Fortran example:

```
real(my_kind), intent(out) :: t
integer :: time_array(8)
…
call date_and_time(values=time_array)
t1 =
   3600.*time_array(5)+60.*time_array(6)+time_array(7)+time_array(
   8)/1000.
do j = 1,n
do k = 1,n
do i = 1,n
c(i,j) = c(i,j) + a(i,k)*b(k,j)
enddo
enddo
enddo
call date_and_time(values=time_array)
t2 =
   3600.*time_array(5)+60.*time_array(6)+time_array(7)+time_array(
   8)/1000.
write(6,*) t2-t1
```

Profilers



There are many versions of commercial profilers, developed by manufacturers of compilers and specialized software house. In addition there are **free profilers**, as those resulting from the GNU, TAU or Scalasca project.



Tau Performance System
- University of Oregon

Intel® VTune™ Amplifier

scalasca

Scalasca
-Research Centre Juelich

The Portland Group PGPROF

GNU gprof

allinea SCALE TO NEW HEIGHTS

OPT

PerfSuite
– National Center for Supercomputing Applications

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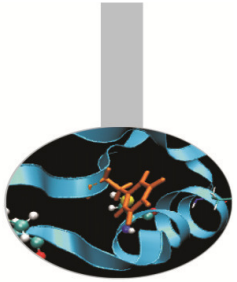
Profilers

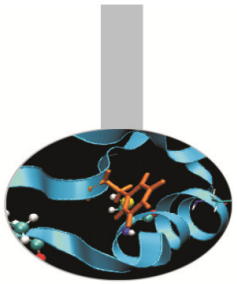


- Profilers allow the programmer to obtain very useful information on the various parts of a code with basically two levels of profiling:

- **Subroutine/Function level**
  - Timing at routine/funcion level, graph of computation flow
  - less intrusive
  - Near realistic execution time

- **Construct/instruction/statement level**
  - capability to profile each instrumented statement
  - more intrusive
  - very accurate timing information
  - longer profiling execution time

GNU Profiler



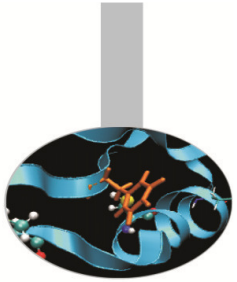
- The GNU profiler “gprof” is an open-source tool that allows profiling of serial and parallel codes.
- GNU profiler how to:
  - Recompile source code using compiler profiling flag:

    ```
    gcc -pg source code
    g++ -pg source code
    gfortran -pg source code
    ```

  - Run the executable to allow the generation of the files containing profiling information:
    - At the end of the execution in the working directory will be generated a specific file generally named “*gmon.out*” containing all the analytic information for the profiler
  - Results analysis

    ```
    gprof executable gmon.out
    ```

GNU Profiler



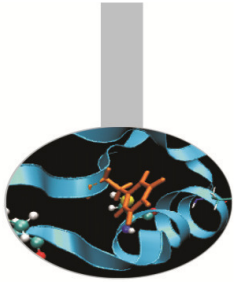
Code is automatically instrumented by the compiler when using the `-pg` flag, during the execution:

- the **number of calls** and the **execution time** of each subroutine is collected
- a call graph containing **dependences between subroutines** is implemented
- a binary file containing above information is generated (**gmon.out**)

The profiler, using data contained in the file *gmon.out,* is able to give precise information about:

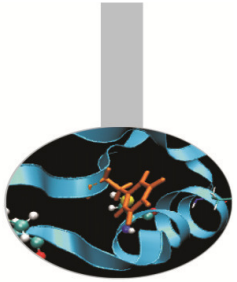
1. the **number of calls** of each routine
2. the **execution time** of a routine
3. the **execution time** of a routine and all the child routines called by that routine
4. a **call graph profile** containing **timing information and relations** between subroutines

Example



```
#include<stdio.h>

double add3(double x){
        return x+3;}

double mysum(double *a, int n){
double sum=0.0;
for(int i=0;i<n;i++)
        sum+=a[i]+add3(a[i]);
return sum;
}

double init(double *a,int n){
double res;
for (int i=0;i<n;i++) a[i]=(double)i;
res=mysum(a,n);
return res;
}

int main(){
double res,mysum;
int n=1000;
double a[n];

for (int i=0;i<n;i++){
        res=init(a,n);
}
printf("Result %f\n",res);
return 0;}
```

Profiler output

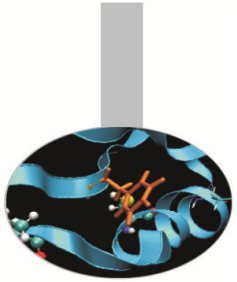


The profiler **gprof** produces two kinds of statistical output: "**flat profile**" and "**call graph profile**".

According to previous example **flat profile** gives the following information:

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 48.60      0.41     0.41    10000    41.31    81.61  init(double*, int)
 27.26      0.64     0.23    10000    23.17    40.30  mysum(double*, int)
 20.15      0.82     0.17 100000000     0.00     0.00  add3(double)
```

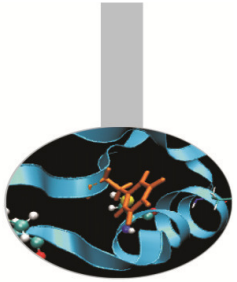
Flat profile



The meaning of the columns displayed in the **flat profile** is:

- **% time**: percentage of the total execution time your program spent in this function
- **cumulative seconds**: cumulative total number of seconds the computer spent executing this functions, plus the time spent in all the functions above this one in this table
- **self seconds**: number of seconds accounted for by this function alone.
- **calls**: total number of times the function was called
- **self us/calls**: represents the average number of microseconds spent in this function per call
- **total us/call**: represents the average number of microseconds spent in this function and its descendants per call if this function is profiled, else blank
- **name**: name of the function

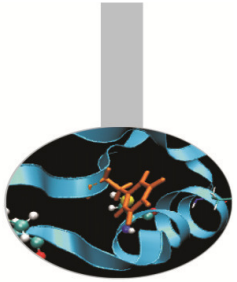
Call Graph



- **Call Graph Profile**: gives more detailed timing and calling sequence information through a dependency call graph.

```
Call graph (explanation follows)

index % time    self  children    called     name

[1]     96.4    0.00    0.82                 main [1]
                0.41    0.40   10000/10000       init(double*, int) [2]
-----------------------------------------------
                0.41    0.40   10000/10000       main [1]
[2]     96.4    0.41    0.40   10000         init(double*, int) [2]
                0.23    0.17   10000/10000       mysum(double*, int) [3]
-----------------------------------------------
                0.23    0.17   10000/10000       init(double*, int) [2]
[3]     47.6    0.23    0.17   10000         mysum(double*, int) [3]
                0.17    0.00 100000000/100000000     add3(double) [4]
-----------------------------------------------
                0.17    0.00 100000000/100000000     mysum(double*, int)
[3]
[4]     20.2    0.17    0.00 100000000          add3(double) [4]
-----------------------------------------------
```

Line level profiling



If necessary it's possible to profile single lines or blocks of code with the GNU pofiler used together with the *"gcov"* tool to see:

- lines that are most frequently accessed
- computationally critical statements or regions

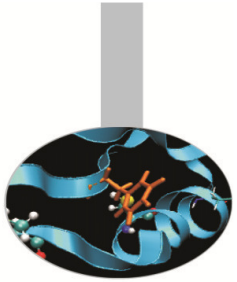
Line level profiling with gcov requires the following steps

- compile with `-fprofile-arcs -ftest-coverage`
  At the end of compilation files `*.gcno` will be produced
- Run the executable. The execution will produce `*.gcda` files
- Run `gcov: gcov [options] sourcefiles`
- At the end of running in the working directory will be present a specific file with extension `*.gcov` which contains all the analytic information for the profiler

NOTES:

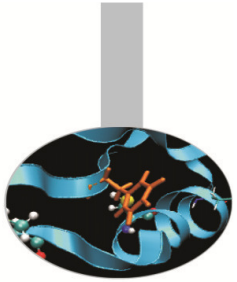
- `gcov` is compatible only with code compiled with GNU compilers
- use low level optimization flags.

Example



```
#include <stdlib.h>
#include <stdio.h>

int prime (int num);
 int main()
 {
        int i;
        int cnt = 0;
        for (i=2; i <= 1000000; i++)
                if (prime(i)) {
                 cnt++;
                if (cnt%9 == 0) {
                        printf("%5d\n",i);
                        cnt = 0;
                }
                else
                printf("%5d ", i);
                }
        putchar('\n');
        if (i<2)
         printf("OK\n");
        return 0;
 }

int prime (int num) {
 int i;
 for (i=2; i < num; i++)
        if (num %i == 0) return 0;
 return 1;
 }
```

Example



Routine level profiling produces the following information:

Each sample counts as 0.01 seconds.

% time	cumulative seconds	self seconds	calls	self us/call	total us/call	name
100.99	109.74	109.74	999999	109.74	109.74	prime(int)

call-graph output:

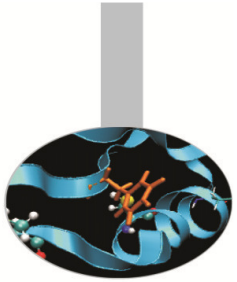
granularity: each sample hit covers 2 byte(s) for 0.01% of 109.74 seconds

index	% time	self	children	called	name
[1]	100.0	0.00	109.74		main [1]
		109.74	0.00	999999/999999	prime(int) [2]

		109.74	0.00	999999/999999	main [1]
[2]	100.0	109.74	0.00	999999	prime(int) [2]

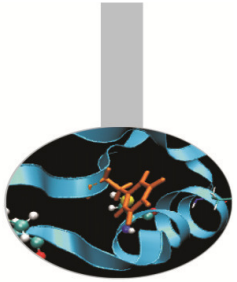
How is time effectively spent in routine `prime`??

Example



```
        -:    1:#include <stdlib.h>
        -:    2:#include <stdio.h>
        -:    3:
        -:    4:int prime (int num);
        -:    5:
        1:    6:int main()
        -:    7: {
        -:    8:        int i;
        1:    9:        int cnt = 0;
  1000000:   10:        for (i=2; i <= 1000000; i++)
   999999:   11:                if (prime(i)) {
    78498:   12:                cnt++;
    78498:   13:                if (cnt%9 == 0) {
     8722:   14:                        printf("%5d\n",i);
     8722:   15:                        cnt = 0;
        -:   16:                }
        -:   17:                else
    69776:   18:                printf("%5d ", i);
        -:   19:                }
        1:   20:        putchar('\n');
        1:   21:        if (i<2)
    #####:   22:                printf("OK\n");
        1:   23:        return 0;
        -:   24: }
        -:   25:
   999999:   26:int prime (int num) {
        -:   27: /* check to see if the number is a prime? */
        -:   28: int i;
37567404990:   29: for (i=2; i < num; i++)
37567326492:   30:      if (num %i == 0) return 0;
    78498:   31: return 1;
        -:   32: }
```

Example



Line level profiling shows that most of time is spent in the `for` loop and in the `if` construct contained in the `prime` function.

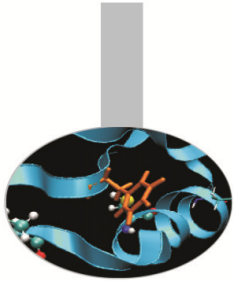
Let's check for a more efficient algorithm.

If a number "n" is not a prime, it can be factored into two factors "a" and "b" : n = a*b

If both a and b were greater than the square root of n, a*b would be greater than n. **So at least one of those factors must be less or equal to the square root of n**, and to check if n is prime, we only need to test for factors less than or equal to the square root.

```
int prime (int num) {
/* check to see if the number is a prime? */
   int i;
   for (i=2; i <= faster(num); i++)
   if (num %i == 0)
         return 0;
   return 1;
}
int faster (int num)
{
   return (int) sqrt( (float) num);
}
```

Example



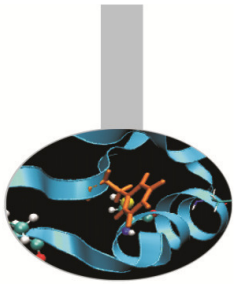
```
      1:    7:int main(){
      -:    8: int i;
      1:    9: int colcnt = 0;
1000000:   10: for (i=2; i <= 1000000; i++)
 999999:   11: if (prime(i)) {
  78498:   12: colcnt++;
  78498:   13: if (colcnt%9 == 0) {
   8722:   14: printf("%5d\n",i);
   8722:   15: colcnt = 0;
      -:   16: }
      -:   17: else
  69776:   18: printf("%5d ", i);
      -:   19: }
      1:   20: putchar('\n');
      1:   21: return 0;
      -:   22: }
      -:   23:
 999999:   24: int prime (int num) {
      -:   25: int i;
67818902:   26: for (i=2; i <= faster(num); i++)
67740404:   27: if (num %i == 0)
 921501:   28:         return 0;
  78498:   29: return 1;
      -:   30: }
      -:   31:
67818902:   32: int faster (int num)
      -:   33: {
67818902:   34: return (int) sqrt( (float) num);
      -:   35: }
```

Results

0.96 sec Vs 109.67 sec

10^7 operations VS 10^10 operations

gprof execution time impact



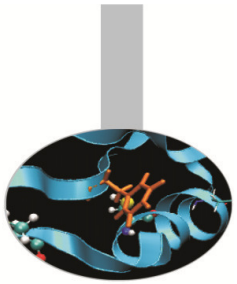
- Routine level and above all line level profiling can cause a certain overhead in execution time:
- Travelling Salesman Problem (TSP):

```
g++ -pg -o tsp_prof tsp.cc
    g++ -o tsp_no_prof tsp.cc
```

- Execution time

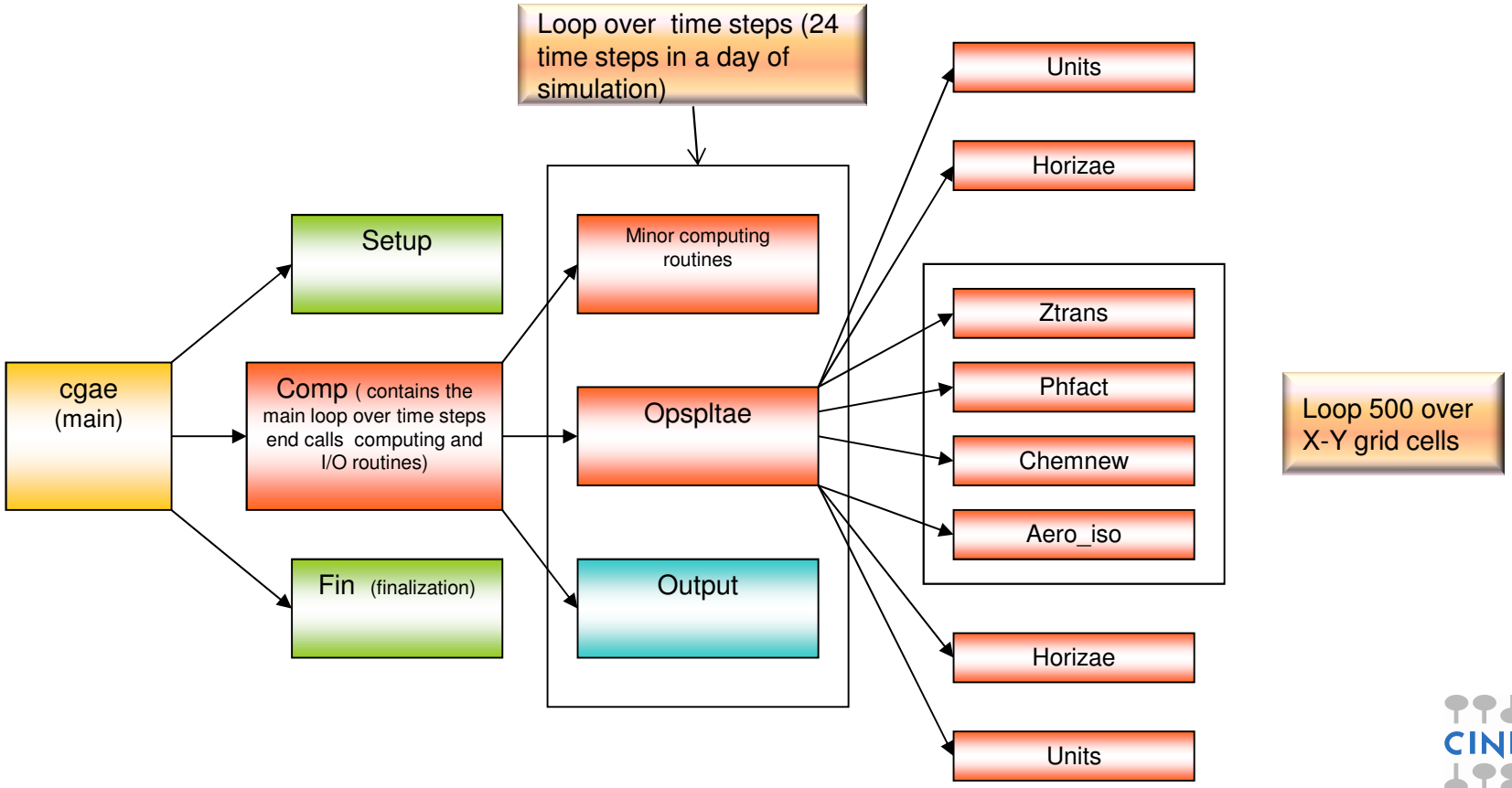
```
time ./TSP.noprof
10.260u 0.000s 0:10.26 100.0%

time ./TSP.prof
15.480u 0.020s 0:15.87 97.6%
```

- **Be careful when you have to choose input dataset and configuration for profiling**

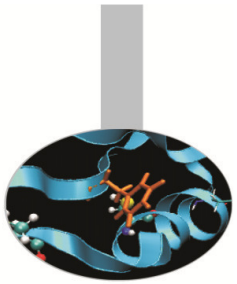


Real case Air Pollution Model

- Model structure and call graph
- Fluid dynamics equations are solved over a 3D grid



Real case Air Pollution Model



- Profiling with GNU profiler (call graph)

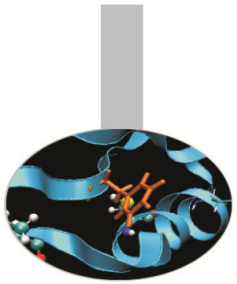
```
index % time    self  children    called     name

 [2]     95.3    0.00 9511.19                 main [2]
                 0.00 9511.19       1/1           MAIN__ [1]
-----------------------------------------------
                 0.00 9507.46       1/1           MAIN__ [1]
[3]     95.2    0.00 9507.46       1         comp_ [3]
               192.03 9047.81     360/360         opspltae_ [4]
               110.52    0.00     360/360         pmcalcdry_ [31]
                59.29    6.23     119/119         aestim_ [33]
                48.95    8.22     120/120         qgridae_ [35]
                19.46    0.00     958/2398        units_ [36]
```

- **5 days of simulation.** Only the computationally intensive routines of the model are shown

- **Dependency call graph of "`opspltae`" routine**

```
index % time    self  children    called     name

               192.03 9047.81     360/360         comp_ [3]
[4]     92.6   192.03 9047.81     360         opspltae_ [4]
                11.71 4346.21 22096800/22096800     chemnew_ [5]
               926.45 2381.89     720/720         horizae_ [10]
               861.92    0.00 8035200/8035200     ztrans_ [15]
                36.54  413.18 22096800/22096800     aero_iso_ [17]
                40.31    0.00 22096800/22096800     phfact_ [39]
                29.26    0.00    1440/2398        units_ [36]
```

Real case air pollution model parallelization strategy

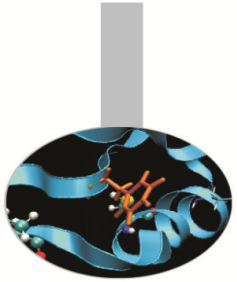


- `Opspltae` is called every time step by "`comp`" and calls `chemnew`, `horizae`, `ztrans`, `aero_iso`, `phfact` and `units` routines. In these routines is spent 92,6% of simulation time.
- The rest of time is spent for initialization, finalization and I/O operations which are not parallelizable of which parallelization doesn't make sense for.
- Ideal speedup obtainable according to profiler output is:

$$S(N) = \frac{1}{(1-P) + \frac{P}{N}} \quad \Rightarrow \quad S(N) = 14$$

- Results
  - Real speedup : 7.6 ☹ **Why?**

Paralle codes profiling with gprof



GNU profiler can be used to profile **parallel codes** but result analysis is not straightforward .

To profile parallel codes the user must follow these steps:

- Set the environment variable `GMON_OUT_PREFIX`

```
export GMON_OUT_PREFIX="profile_data_file"
```

- Compile with "–p" flag:

```
mpic++/mpicc/mpif70/mpif90 -p filenames
```

- Run the executable:

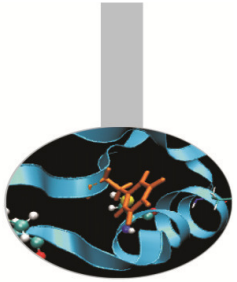
```
mpirun -np number executable
```

At the end of simulation in the working directory will be present as many `profile_data_file.pid` files as MPI or OpenMP processes were used.

Each profiling file must be analyzed and than results have to be matched together:

```
gprof ./executable profile_data_file.pid
```

TAU Tuning and Analysis Utilities



- TAU Performance System® is a portable profiling and tracing toolkit for performance analysis of serial and parallel programs written in Fortran, C, C++, Java, and Python.

  www.cs.uoregon.edu/research/tau

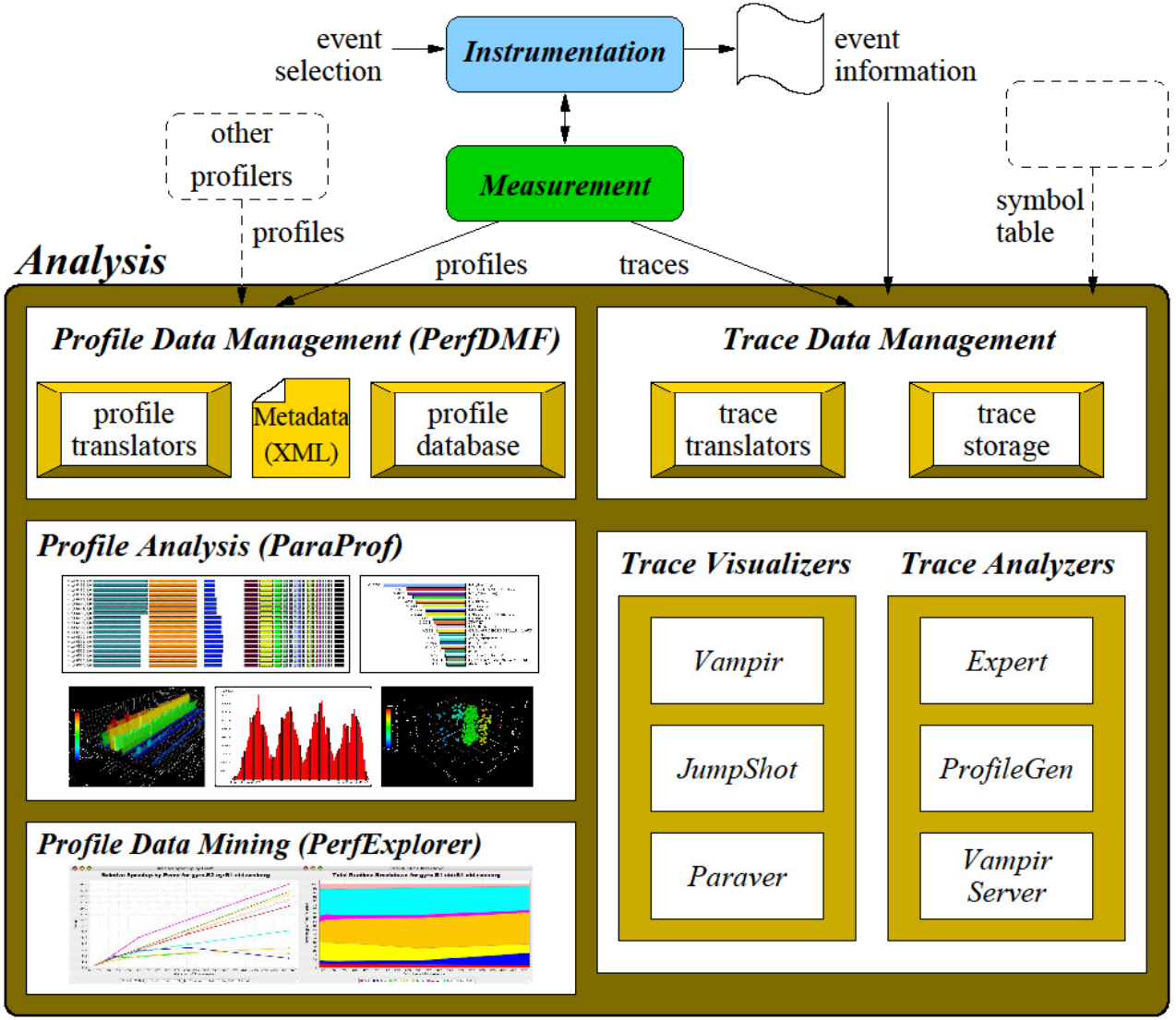
- 12+ years of project in which are currently involved:
  - University of Oregon Performance Research Lab
  - LANL Advanced Computing Laboratory
  - Research Centre Julich at ZAM, Germany

- TAU (Tuning and Analysis Utilities) is capable of gathering performance information through instrumentation of functions, methods, basic blocks and statements of serial and shared or distributed memory parallel codes

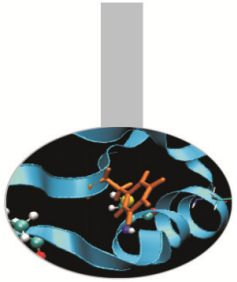
- It's portable on all architectures

- Provides powerful and user friendly graphic tools for result analysis

TAU: architecture



TAU Installation and configuration

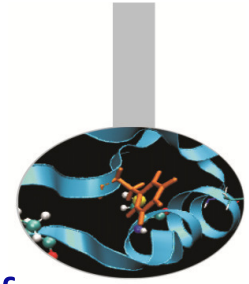


- During the installation phase TAU requires different configurations flags depending on the kind of code to be analyzed.

GNU	Flags
Base Serial	`configure -prefix=/data/apps/bin/tau/2.20.2/gnu/base_serial -pdt=/data/apps_exa/bin/pdt/3.17/intel-c++=g++ -cc=gcc -fortran=gfortran`
Base MPI	`configure -prefix=/data/apps/bin/tau/2.20.2/gnu/base_mpi -mpi -mpiinc=/usr/mpi/gcc/openmpi-1.4.1/include -mpilib=/usr/mpi/gcc/openmpi-1.4.1/lib64 -pdt=/data/apps_exa/bin/pdt/3.17/intel -c++=g++ -cc=gcc -fortran=gfortran`
Base OpenMP	`configure -prefix=/data/apps/bin/tau/2.20.2/gnu/base_openmp -pdt=/data/apps_exa/bin/pdt/3.17/intel -openmp -opari -opari_region -opari_construct -c++=g++ -cc=gcc -fortran=gfortran`
Base MPI+OpenMP	`configure -prefix=/data/apps/bin/tau/2.20.2/gnu/base_mpi_openmp -openmp -mpi -mpiinc=/usr/mpi/gcc/openmpi-1.4.1/include -mpilib=/usr/mpi/gcc/openmpi-1.4.1/lib64 -pdt=/data/apps_exa/bin/pdt/3.17/intel-opari -opari_region -opari_construct -c++=g++ -cc=gcc -fortran=gfortran`

- After configuration TAU can be easily installed with:
  - make
  - make install

TAU: introduction



- TAU provides three different methods to track the performance of your application.
- The simplest way is to use TAU with dynamic instrumentation based on pre-charged libraries

Dynamic instrumentation

- **Doesn't** requires to recompile the executable
- Instrumentation is achieved at **run-time** through library pre-loading
- Dynamic instrumentation include tracking MPI, io, memory, cuda, opencl library calls. MPI instrumentation is included by default, the others are enabled by command-line options to tau_exec.

  – Serial code

  ```
  %> tau_exec -io ./a.out
  ```

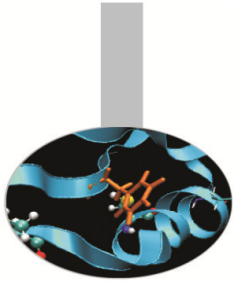
  – Parallel MPI code

  ```
  %> mpirun -np 4 tau_exec -io ./a.out
  ```

  – Parallel MPI + OpenMP code

  ```
  %> mpirun -x OMP_NUM_THREADS=2 -np 4 tau_exec -io ./a.out
  ```

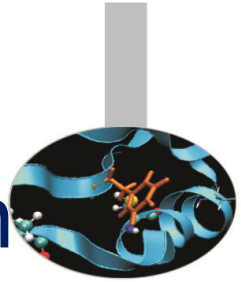
TAU: Compiler based instrumentation



- For more detailed profiles, TAU provides two means to compile your application with TAU: through your compiler or through source transformation using PDT.
- **It's necessary** to recompile the application, **static instrumentation** at compile time

- TAU provides these scripts to instrument and compile Fortran, C,and C++ programs respectively:
  - `tau_f90.sh`
  - `tau_cc.sh`
  - `tau_cxx.sh`
- Compiler based instrumentation needs the following steps:
  - Environment configuration
  - Code recompiling
  - Execution
  - Result analysis

TAU: Compiler based instrumentation



1. Environment configuration:

```
%>export TAU_MAKEFILE=[path to tau]/[arch]/lib/[makefile]
%>export TAU_OPTIONS='-optCompInst -optRevert'
```

Optional:

```
%>export PROFILEDIR = [path to directory with result]
```

2. Code recompiling:

```
%>tau_cc.sh source_code.c
```

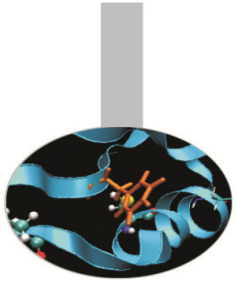
3. To enable callpath creation:

```
%>export TAU_CALLPATH=1
%>export TAU_CALLPATH_DEPTH=30
```

4. To enable MPI message statistics

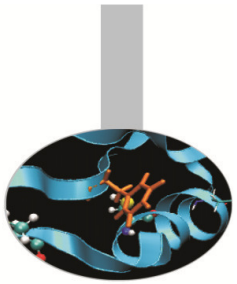
```
%>export TAU_TRACK_MESSAGE=1
```

TAU environment variables



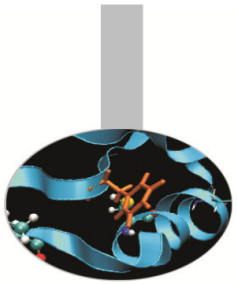
Environment Variable	Default	Description
TAU_PROFILE	1	Set to 1 to have TAU profile your code
TAU_CALLPATH	0	When set to 1 TAU will generate call-path data. Use with TAU_CALLPATH_DEPTH.
TAU_CALLPATH_DEPTH	2	Callapath depth. 0 No callapath. 1 flat profile
TAU_SYNCHRONIZE_CLOCKS	1	When set TAU will correct for any time discrepancies between nodes because of their CPU clock lag.
TAU_COMM_MATRIX	0	If set to 1 generate MPI communication matrix data.
TAU_THROTTLE	1	If set to 1 enables the runtime throttling of events that are lightweight
TAU_THROTTLE_NUMCALLS	100000	Set the maximum number of calls that will be profiled for any function when TAU_THROTTLE is enabled
TAU_THROTTLE_PERCALL	10	Set the minimum inclusive time (in milliseconds) a function has to have to be instrumented when TAU_THROTTLE is enabled.

TAU_OPTIONS



- Optional parameters for TAU_OPTIONS: [tau_compiler.sh –help]
  - -optVerbose — Vebose debugging
  - -optCompInst — Compiler based instrumentation
  - -optNoCompInst — No Compiler based instrumentation
  - -optPreProcess — Fortran preprocessing before code instrumentation
  - -optTauSelectFile=“ " — Selective file for the tau_instrumentor

Result analysis



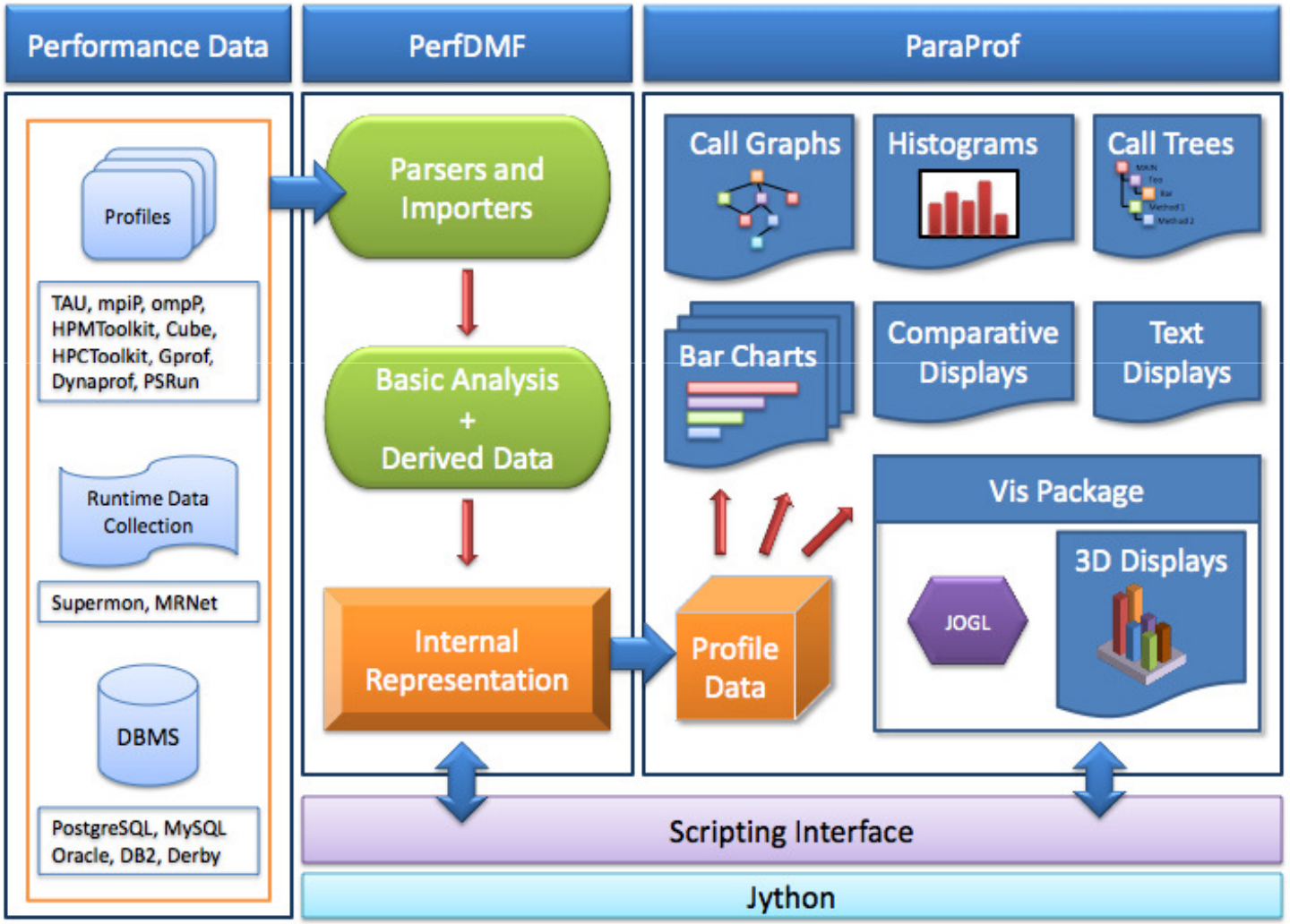
- At the end of a run, a code instrumented with TAU produces a series of files "`profile.x.x.x`" containing the profiling information.

- TAU provides two tools for profiling analysis :
  - `pprof` command line, useful for a quick view summary of TAU performance
  - `Paraprof` with a sophisticated GUI allows very detailed and powerful analysis

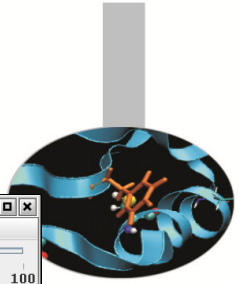
- **Usage:** `pprof [-c|-b|-m|-t|-e|-i|-v] [-r] [-s] [-n num] [-f filename] [-p] [-l] [-d] [node numbers]`

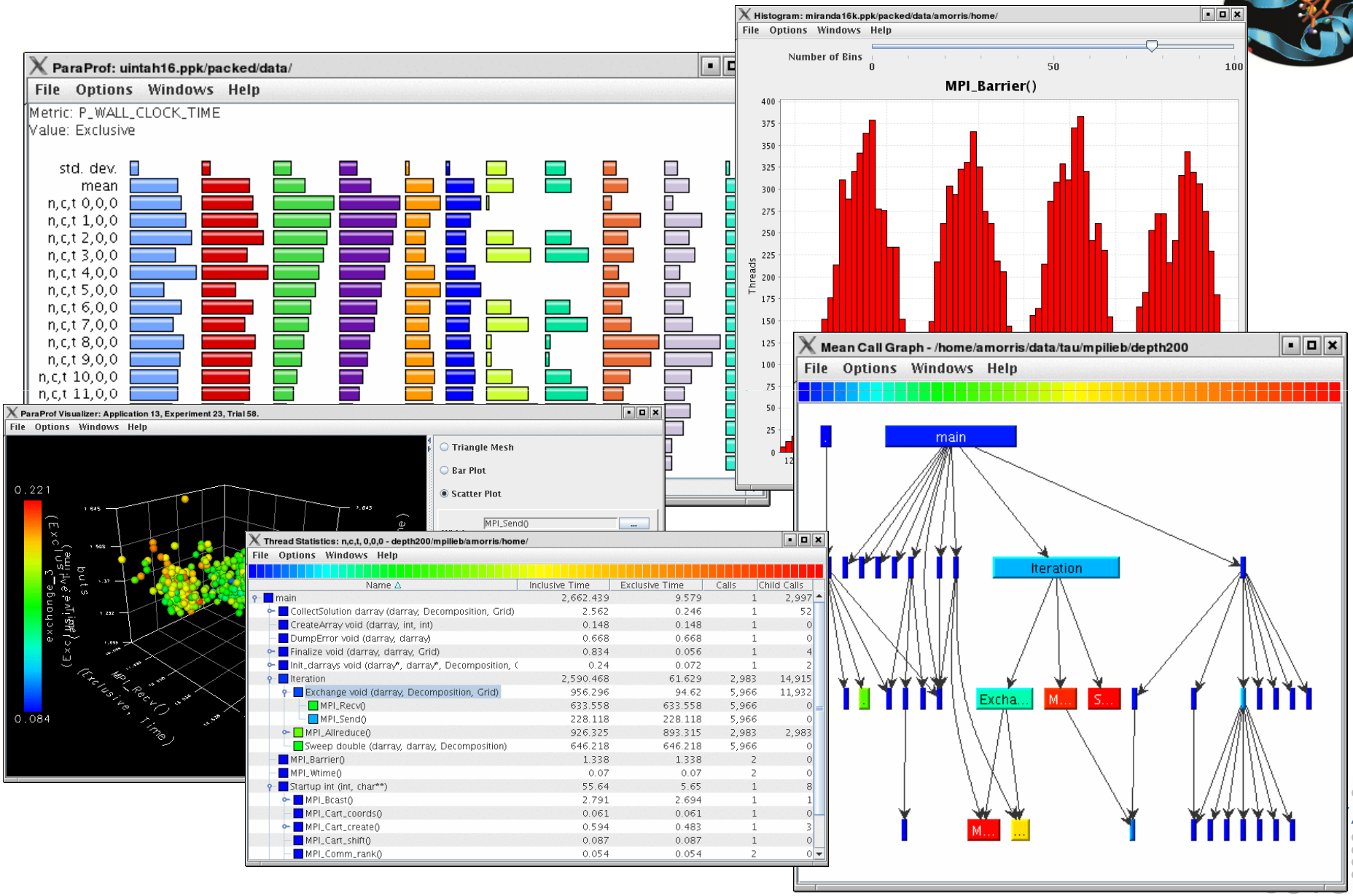
```
-a : Show all location information available
-c : Sort according to number of Calls
-b : Sort according to number of suBroutines called by a function
-m : Sort according to Milliseconds (exclusive time total)
-t : Sort according to Total milliseconds (inclusive time total)
  (default)
-e : Sort according to Exclusive time per call (msec/call)
-i : Sort according to Inclusive time per call (total msec/call)
-v : Sort according to Standard Deviation (excl usec)
-r : Reverse sorting order
-s : print only Summary profile information
-n <num> : print only first <num> number of functions
-f filename : specify full path and Filename without node ids
-p : suPpress conversion to hh:mm:ss:mmm format
-l : List all functions and exit
-d : Dump output format (for tau_reduce) [node numbers] : prints only
  info about all contexts/threads of given node numbers
```

Result analysis: paraprof

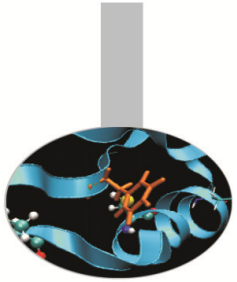


Paraprof



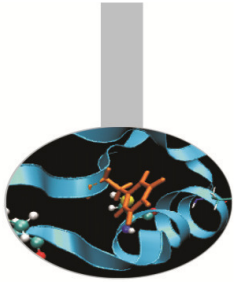

ParaProf: uintah16.ppk/packed/data/
File Options Windows Help
Metric: P_WALL_CLOCK_TIME
Value: Exclusive
std. dev.
mean
n,c,t 0,0,0
n,c,t 1,0,0
n,c,t 2,0,0
n,c,t 3,0,0
n,c,t 4,0,0
n,c,t 5,0,0
n,c,t 6,0,0
n,c,t 7,0,0
n,c,t 8,0,0
n,c,t 9,0,0
n,c,t 10,0,0
n,c,t 11,0,0
Histogram: miranda16k.ppk/packed/data/amorris/home/
File Options Windows Help
Number of Bins
0
50
100
MPI_Barrier()
Threads
Mean Call Graph - /home/amorris/data/tau/mpilieb/depth200
File Options Windows Help
main
Iteration
Excha...
M...
S...
M...
ParaProf Visualizer: Application 13, Experiment 23, Trial 58.
File Options Windows Help
Triangle Mesh
Bar Plot
Scatter Plot
MPI_Send()
0.221
0.084
Thread Statistics: n,c,t, 0,0,0 - depth200/mpilieb/amorris/home/
File Options Windows Help
Name
Inclusive Time
Exclusive Time
Calls
Child Calls
main 2,662.439 9.579 1 2,997
CollectSolution darray (darray, Decomposition, Grid) 2.562 0.246 1 52
CreateArray void (darray, int, int) 0.148 0.148 1 0
DumpError void (darray, darray) 0.668 0.668 1 0
Finalize void (darray, darray, Grid) 0.834 0.056 1 4
Init_darrays void (darray*, darray*, Decomposition, 0.24 0.072 1 2
Iteration 2,590.468 61.629 2,983 14,915
Exchange void (darray, Decomposition, Grid) 956.296 94.62 5,966 11,932
MPI_Recv() 633.558 633.558 5,966 0
MPI_Send() 228.118 228.118 5,966 0
MPI_Allreduce() 926.325 893.315 2,983 2,983
Sweep double (darray, darray, Decomposition) 646.218 646.218 5,966 0
MPI_Barrier() 1.338 1.338 2 0
MPI_Wtime() 0.07 0.07 2 0
Startup int (int, char**) 55.64 5.65 1 8
MPI_Bcast() 2.791 2.694 1 1
MPI_Cart_coords() 0.061 0.061 1 0
MPI_Cart_create() 0.594 0.483 1 3
MPI_Cart_shift() 0.087 0.087 1 0
MPI_Comm_rank() 0.054 0.054 2 0

Example



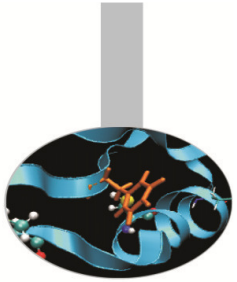
```
#include<stdio.h>

double add3(double x){
        return x+3;}

double mysum(double *a, int n){
double sum=0.0;
for(int i=0;i<n;i++)
        sum+=a[i]+add3(a[i]);
return sum;
}

double init(double *a,int n){
double res;
for (int i=0;i<n;i++) a[i]=(double)i;
res=mysum(a,n);
return res;
}

int main(){
double res,mysum;
int n=30000;
double a[n];

for (int i=0;i<n;i++){
        res=init(a,n);
}
printf("Result %f\n",res);
return 0;}
```

Pprof



`pprof` output:

```
%> pprof

Reading Profile files in profile.*

NODE 0;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------
100.0           3     3:20.342           1           1  200342511 .TAU application
100.0           4     3:20.338           1       30000  200338851 main
100.0       2,344     3:20.334       30000       30000       6678 init
 98.8    1:40.824     3:17.989       30000       9E+08       6600 mysum
 48.5    1:37.164     1:37.164       9E+08           0          0 add3
```



Paraprof Manager Window

`paraprof` **output:**

TAU: ParaProf Manager

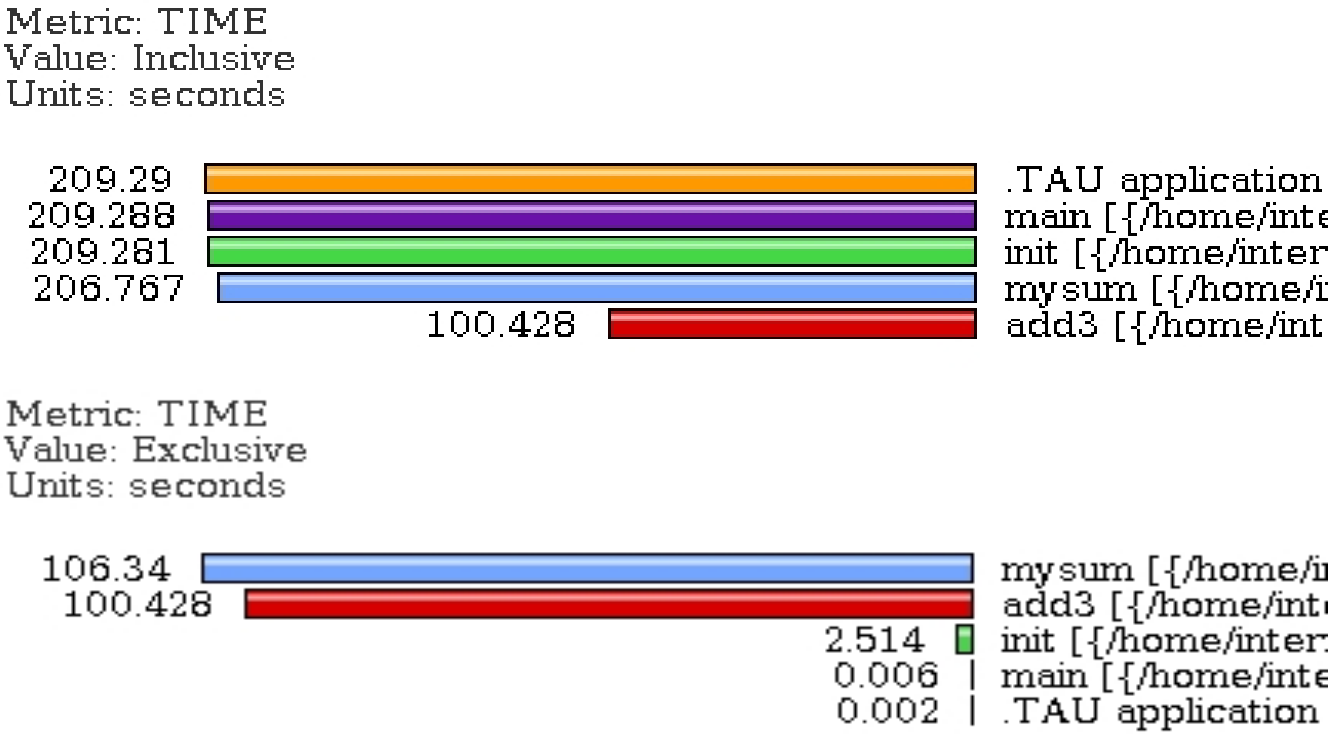
File Options Help

- Applications
  - Standard Applications
    - Default App
      - Default Exp
        - profiling/esercizi_scuola_dottorato
          - TIME

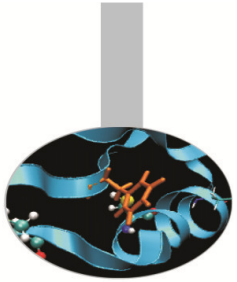
TrialField	Value
Name	profiling/esercizi_scuola_dottorato/d...
Application ID	0
Experiment ID	0
Trial ID	0
CPU Cores	6
CPU MHz	2799.310
CPU Type	Intel(R) Xeon(R) CPU X5660 @ 2.80G...
CPU Vendor	GenuineIntel
CWD	/home/interni/dagna/esercizi_scuola...
Cache Size	12288 KB
Command Line	./sum_tau
Executable	/home/interni/dagna/esercizi_scuola...
File Type Index	1
File Type Name	Tau profiles
Hostname	cn298
Local Time	2012-05-14T09:54:56+02:00
Memory Size	24683248 kB
Node Name	cn298
OS Machine	x86_64
OS Name	Linux
OS Release	2.6.18-238.el5
OS Version	#1 SMP Sun Dec 19 14:22:44 EST 2...
Starting Timestamp	1336982065530947
TAU Architecture	x86_64
TAU Config	-prefix=/data/apps/bin/tau/2.20.2...
TAU Makefile	/data/apps/bin/tau/2.20.2/gnu/bas...
TAU Version	2.20.2
TAU_CALLPATH	on

This window is used to manage profile data. The user can upload/download profile data, edit meta-data, launch visual displays, export data, derive new metrics, etc.

Thread bar chart

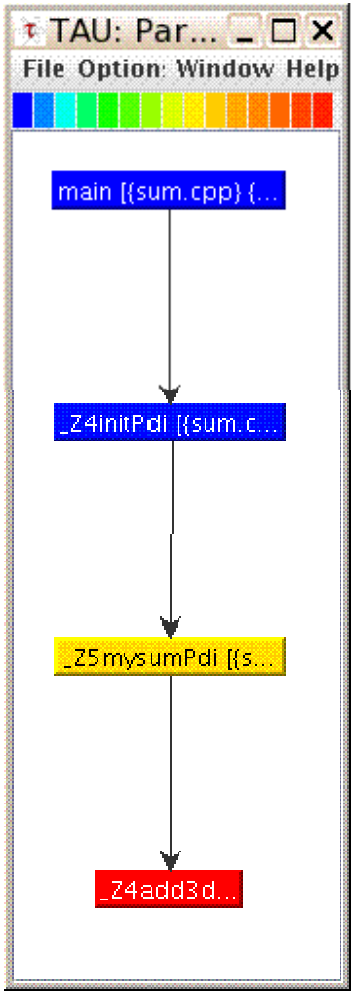


This display graphs each function on a particular thread for comparison. The metric, units, and sort order can be changed from the **Options** menu.

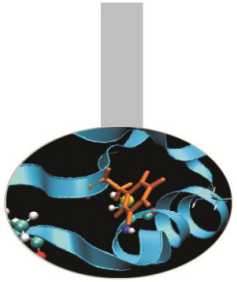


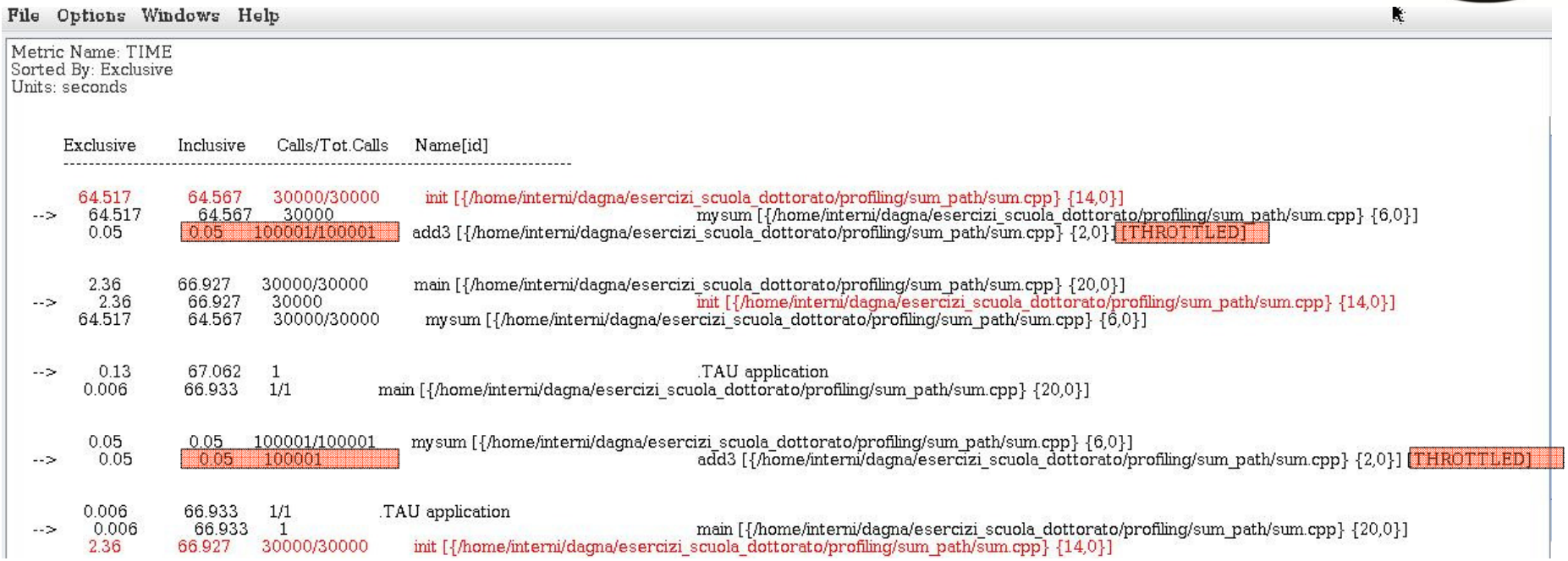
Call Graph

- This display shows callpath data in a graph using two metrics, one determines the width, the other the color.
- The full name of the function as well as the two values (color and width) are displayed in a tooltip when hovering over a box.
- By clicking on a box, the actual ancestors and descendants for that function and their paths (arrows) will be highlighted with blue.
- This allows you to see which functions are called by which other functions since the interplay of multiple paths may obscure it.



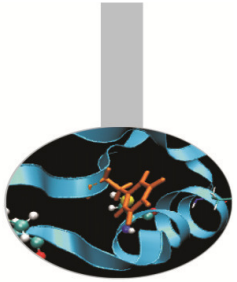
Thread Call Path Relations Window





- For example “mysum” is called from “init” 30000 times for a total of 64.5 seconds and calls “add3” function.
- TAU automatically throttles short running functions in an effort to reduce the amount of overhead associated with profiles of such functions, default throttle limit is:
  - numcalls> 100000 && usecs/call < 10
- To change default settings TAU gives the following environment variables:
  - TAU_THROTTLE_NUMCALLS, TAU_THROTTLE_PERCALL
- To disable TAU throttle : export TAU_THROTTLE=0

Thread Statistics Table



TAU: ParaProf: Thread Statistics: n,c,t, 0,0,0 - /home/interni/dagna/bando_lisa/lisa043/DriCavBHS/test_8...

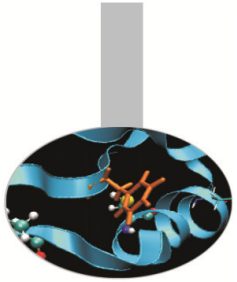
File Options Windows Help

Name	Exclusive TIME	Inclusive TIME	Calls	Child Calls
TAU application	0.027	237.493	1	1
MAIN__ [{/home/interni/dagna/bando_lisa/lisa043/DriCavBHS/test_8nodi_2mpixno	17.316	237.466	1	262
MPI_Comm_rank()	0	0	1	0
MPI_Comm_size()	0	0	1	0
MPI_Finalize()	0.027	0.027	1	0
MPI_Init()	1.457	1.457	1	0
MPI_Send()	0.227	0.227	240	0
collision_ [{/home/interni/dagna/bando_lisa/lisa043/DriCavBHS/test_8nodi_2mpi	129.422	217.117	9	639
MPI_Allreduce()	0.031	0.031	36	0
MPI_Bcast()	0.247	0.247	36	0
MPI_Recv()	87.412	87.412	540	0
MPI_Reduce()	0.006	0.006	27	0
streaming_ [{/home/interni/dagna/bando_lisa/lisa043/DriCavBHS/test_8nodi_2r	1.322	1.322	9	0

This display shows the callpath data in a table. Each callpath can be traced from root to leaf by opening each node in the tree view.

A colorscale immediately draws attention to "hot spots" areas that contain highest values.

Tau profiler: parallel codes



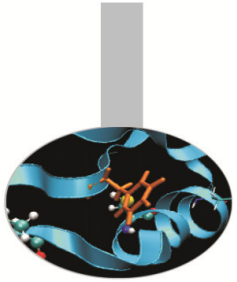
TAU provides a lot of tools to analyze OpenMP, MPI or OpenMP + MPI parallel codes.

Profiling the application the user can obtain a lot of useful information which can help to identify the causes of an unexpected low parallel efficiency.

Principal factors which can affect parallel efficiency are:

- load balancing
- communication overhead
- process synchronization
- Latency and bandwidth

Tau profiler: parallel codes



- Configure:

```
%>export TAU_MAKEFILE=[path to tau]/[arch]/lib/[makefile]
%>export TAU_OPTIONS=-optCompInst
```

- Compile:

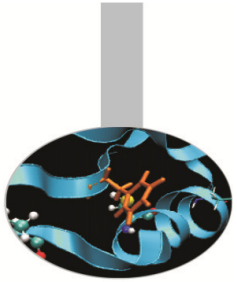
```
Tau_cc.sh -o executable source.c     (C)
Tau_cxx.sh -o executable source.cpp (C++)
Tau_f90.sh -o executable source.f90 (Fortran)
```

- Run the application:

```
mpirun -np #procs ./executable
```

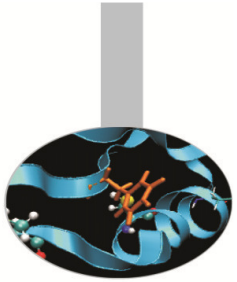
At the end of simulation, in the working directory or in the path specified with the `PROFILEDIR` variable, the data for the profiler will be saved in files `profile.x.x.x`

Unbalanced load



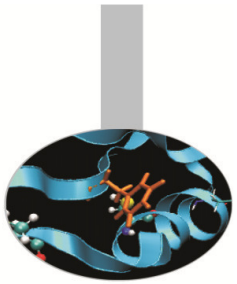
```
# include <cstdlib>
# include <iostream>
# include <iomanip>
# include <cmath>
using namespace std;

# include "mpi.h"
void compute(float * data, int start, int stop){

        for (int i=0;i<1000000;i++){
                for(int j=start;j<stop;j++){
                        data[j]=pow((double)j/(j+4),3.5);}}
}
int main ( int argc, char *argv[] )
 {
  int count;
  float data[24000];
  int dest,i,num_procs,rank,tag;
  MPI::Status status;
  float value[12000];

   MPI::Init ( argc, argv );
   rank = MPI::COMM_WORLD.Get_rank ( );
   if ( rank == 0 )
  {
    num_procs = MPI::COMM_WORLD.Get_size ( );

    cout << "  The number of processes available is " << num_procs << "\n";
  }
```

Unbalanced load



```
if ( rank == 0 )
  {
    tag = 55;
    MPI::COMM_WORLD.Recv ( value,12000, MPI::FLOAT, MPI::ANY_SOURCE, tag,
      status );

    cout << "P:" << rank << " Got data from process " <<
      status.Get_source() << "\n";

    count = status.Get_count ( MPI::FLOAT );

    cout << "P:" << rank << " Got " << count << " elements.\n";

    compute(value,0,12000);
  }
else if ( rank == 1 )
  {
    cout << "\n";
    cout << "P:" << rank << " - setting up data to send to process 0.\n";

    for ( i = 0; i <24000; i++ )
    {
      data[i] = i;
    }
    dest = 0;
    tag = 55;
    MPI::COMM_WORLD.Send ( data, 12000, MPI::FLOAT, dest, tag );
    compute(data,12000,24000);
  }
```

Unbalanced load

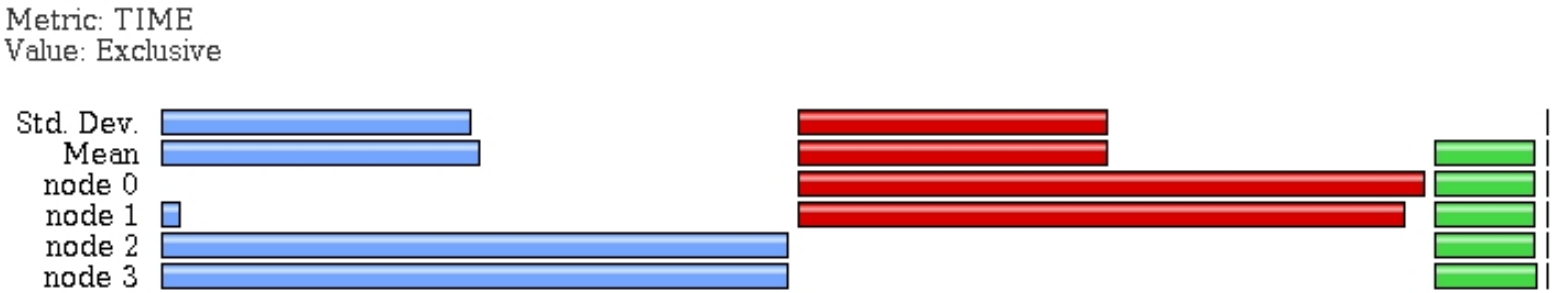


```
else
  {
    cout << "\n";
    cout << "P:" << rank << " - MPI has no work for me!\n";
  }
  MPI::Finalize ( );
  if ( rank == 0 )
  {
    cout << "  Normal end of execution.\n";
  }
  return 0;
}
```

Output:

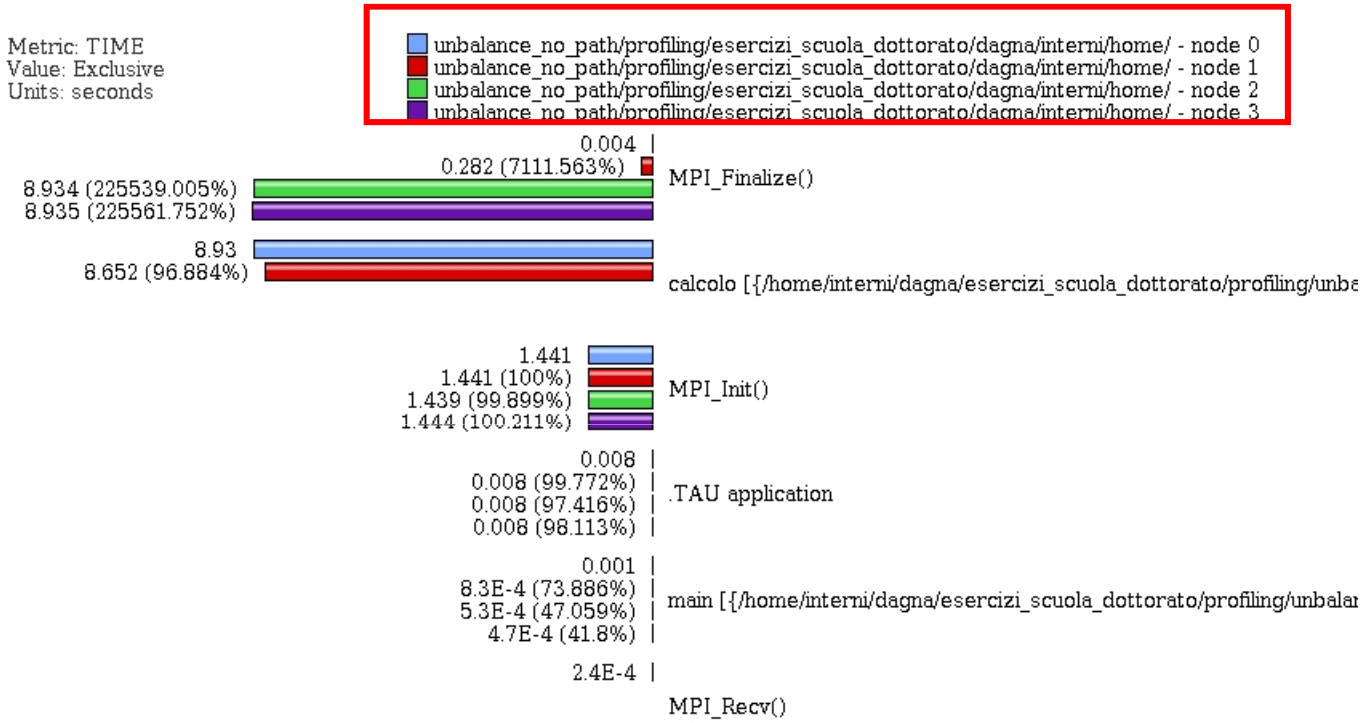
```
The number of processes available is 4
P:0 Got data from process 1
P:0 Got 12000 elements.

P:1 - setting up data to send to process 0.

P:3 - MPI has no work for me!

P:2 - MPI has no work for me!
Normal end of execution.
```

Unstacked bars



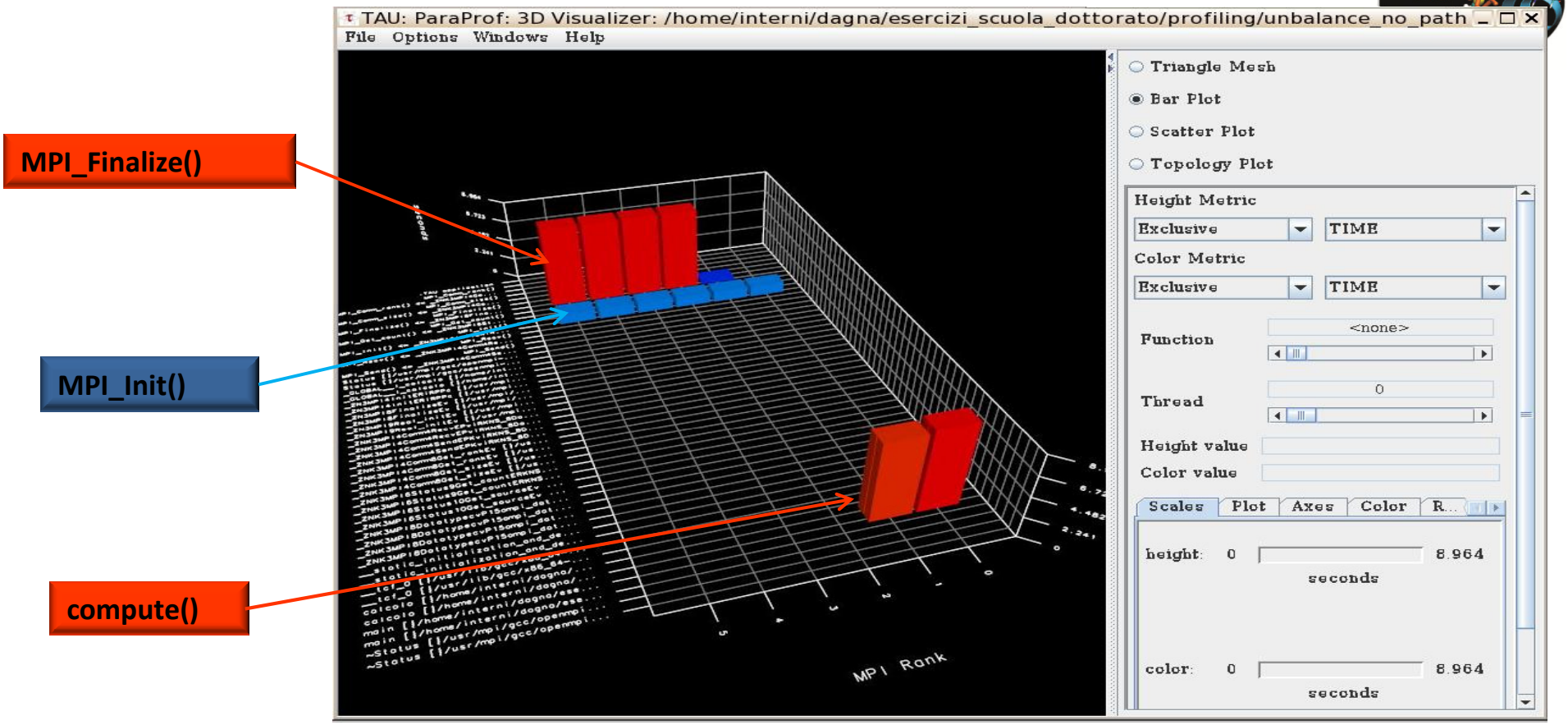
- Very useful to compare individual functions across threads in a global display

Comparison window



Very useful to compare the behavior of process and threads in all the functions or regions of the code to find load unbalances.

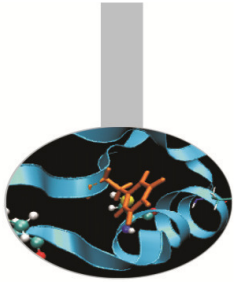
3D Visualizer



This visualization method shows two metrics for all functions, all threads. The height represents one chosen metric, and the color, another. These are selected from the drop-down boxes on the right.

To pinpoint a specific value in the plot, move the *Function* and *Thread* sliders to cycle through the available functions/threads.

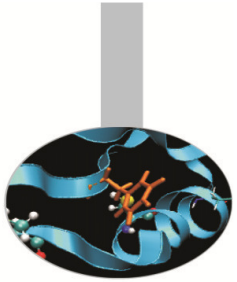
Balanced load



Balancing the load:

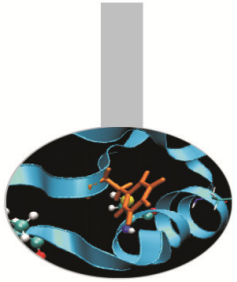
```
int main ( int argc, char *argv[] )
{
MPI::Init ( argc, argv );
rank = MPI::COMM_WORLD.Get_rank ( );
float data[24000];

  if ( rank == 0 )
  {
    num_procs = MPI::COMM_WORLD.Get_size ( );

    cout << "  The number of processes available is " << num_procs << "\n";
  }
  int subd = 24000/num_procs
  if ( rank!= 0)
  {
    tag = 55;
    MPI::COMM_WORLD.Recv ( data,subd, MPI::FLOAT, MPI::ANY_SOURCE, tag, status );

    cout << "P:" << rank << " Got data from process " <<
      status.Get_source() << "\n";
    count = status.Get_count ( MPI::FLOAT );

    cout << "P:" << rank << " Got " << count << " elements.\n";
    compute(data,rank*subd,rank*subd+subd);
    printf("Done\n");
  }
```

Balanced load



```
else if ( rank == 0 )
  {
    cout << "\n";
    cout << "P:" << rank << " - setting up data to send to processes.\n";

    for ( i = 0; i <24000; i++ )
    {
      data[i] = i;
    }

    tag = 55;
    printf("Done\n");
    for(int el=1;el<num_procs;el++){

        MPI::COMM_WORLD.Send ( &data[subd*el], subd, MPI::FLOAT, el, tag );
    }

    compute(data,0,subd);
  }

  MPI::Finalize ( );

  if ( rank == 0 )
  {
    cout << "  Normal end of execution.\n";
  }

  return 0;
}
```

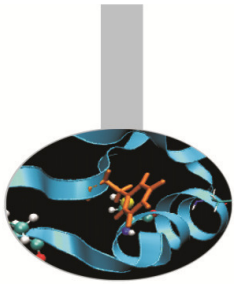
Balanced load



- Output:

```
 The number of processes available is 6

P:0 - setting up data to send to processes.
Done
P:5 Got data from process 0
P:5 Got 4000 elements.
P:1 Got data from process 0
P:1 Got 4000 elements.
P:2 Got data from process 0
P:2 Got 4000 elements.
P:3 Got data from process 0
P:3 Got 4000 elements.
P:4 Got data from process 0
P:4 Got 4000 elements.
Done
Done
Done
Done
Done
  Normal end of execution.
```

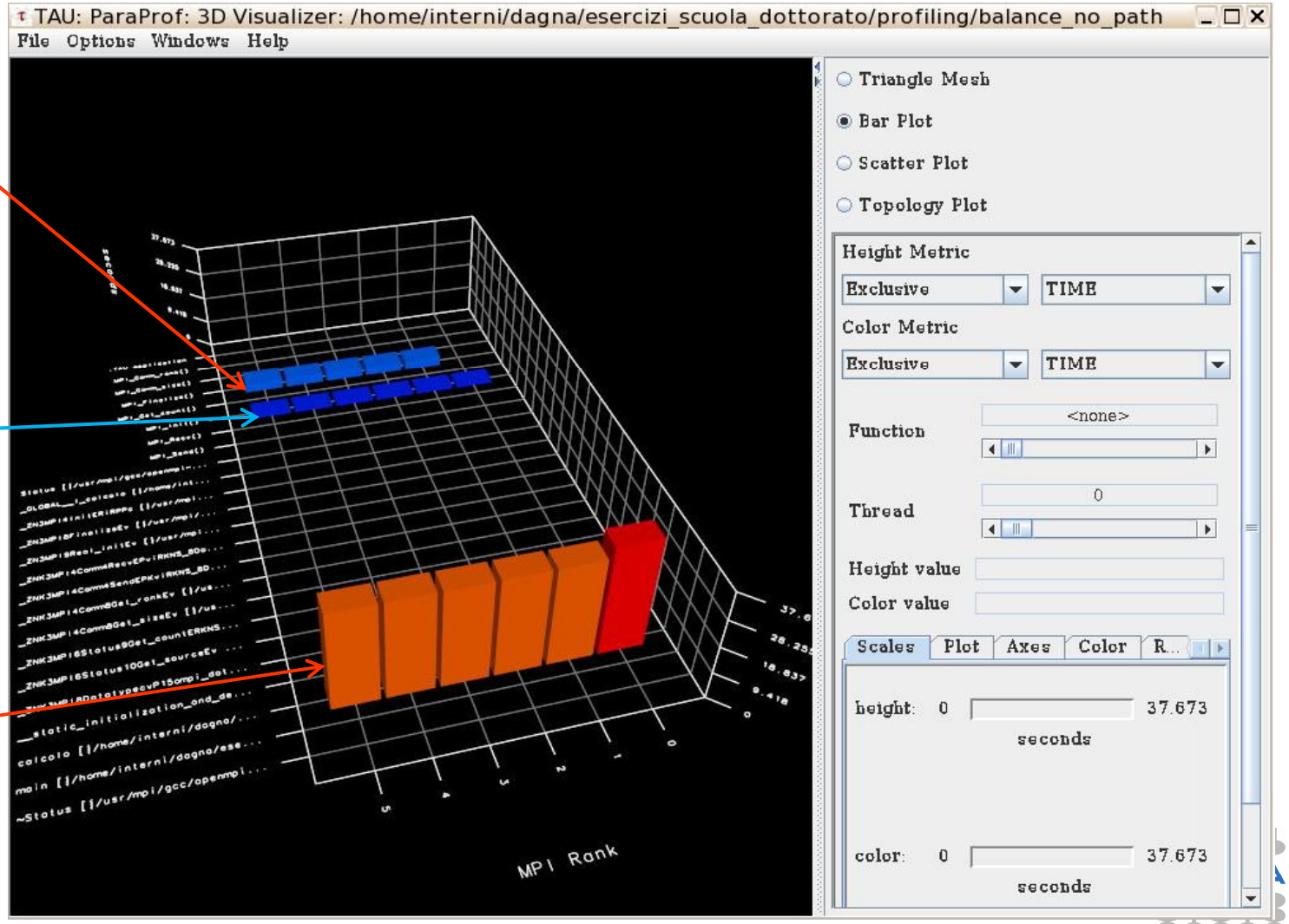
Balanced load



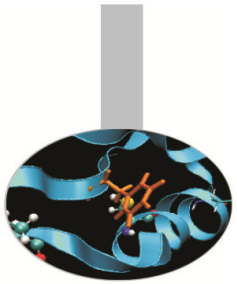
MPI_Finalize()

MPI_Init()

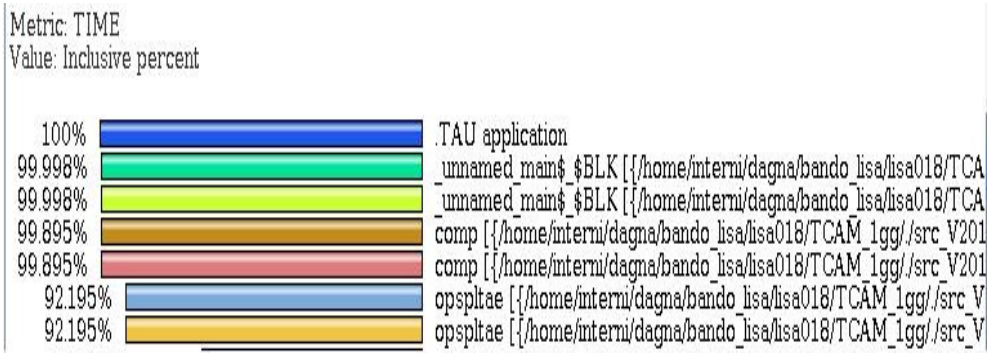
compute()



Real Case Air Pollution Model

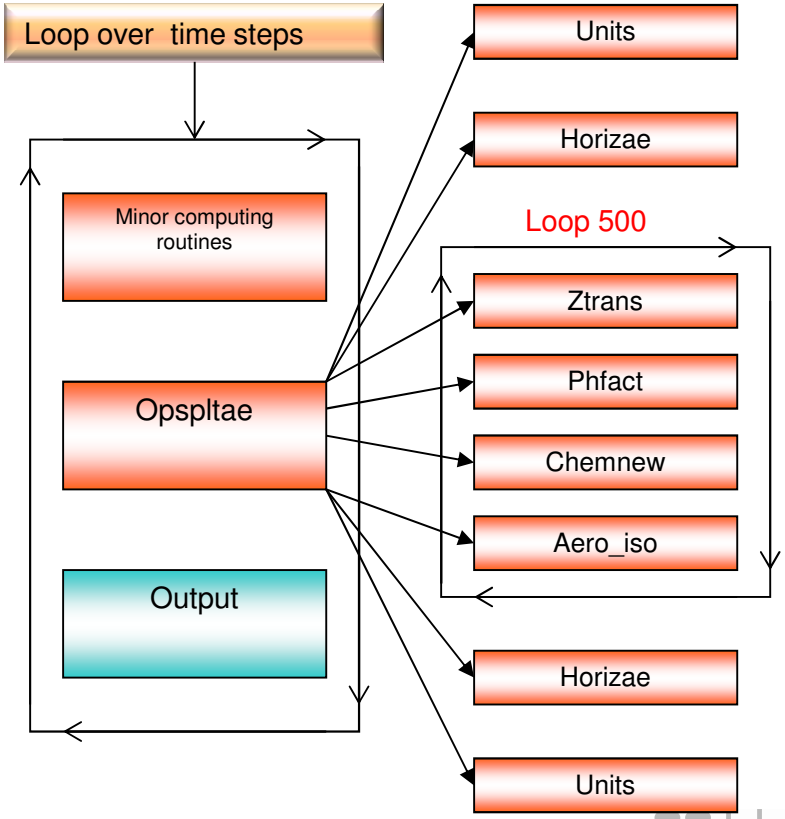


Metric: TIME
Value: Inclusive percent

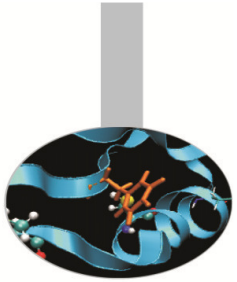


Metric: TIME
Sorted By: Exclusive
Units: seconds

	Exclusive	Inclusive	Calls/Tot.Calls	
	71.785	3829.47	72/72	comp [{/home/interni/dagna/bando_lisa/lisa018/T
-->	71.785	3829.47	72	opspltae
	0.248	0.248	100001/100001	phfact [{/home/interni/dagna/bando_lisa/lisa0
	2.4E-4	2.4E-4	72/72	newphknew [{/home/interni/dagna/bando_lisa/lisa
	6.123	6.123	288/478	units [{/home/interni/dagna/bando_lisa/lisa018/T
	6.48	2746.714	4419360/4419360	chemnew [{/home/interni/dagna/bando_lis
	7.8E-4	7.8E-4	72/74	datetm [{/home/interni/dagna/bando_lisa/lisa018/
	80.281	452.527	144/144	horizae [{/home/interni/dagna/bando_lisa/lisa01
	33.933	362.447	4419360/4419360	aero_iso [{/home/interni/dagna/bando_lis
	0.021	0.021	35211/100001	relhum [{/home/interni/dagna/bando_lisa/lisa01
	189.604	189.604	1607040/1607040	ztrans [{/home/interni/dagna/bando_lisa/l
	7.8E-4	7.8E-4	864/938	iaddrs [{/home/interni/dagna/bando_lisa/lisa018
	4.2E-5	4.2E-5	72/72	savphknew [{/home/interni/dagna/bando_lisa/lisaC



Real Case Air Pollution Model



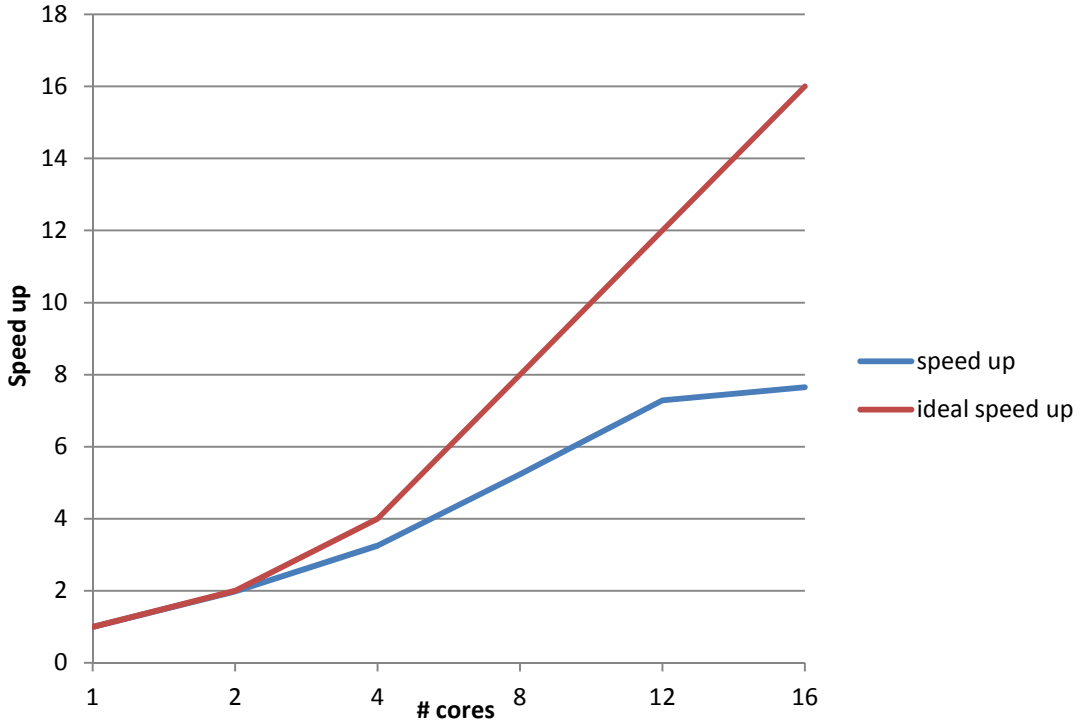
Amdahl law

Theoretical speedup

$$S(N) = \frac{1}{(1-P) + \frac{P}{N}}.$$

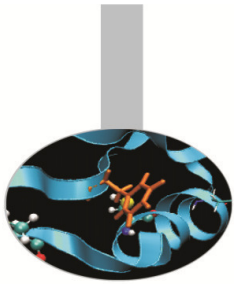
P=0.93 ➔ S(N)=14

Real speedup = 7.6 ☹



Let's check communication and load balncing !!

Real Case Air Pollution Model



Master process

opspltae [{/home/interni/	3.855	451.743	72	700,772
MPI_Bcast()	6.751	6.751	648	0
MPI_Comm_rank()	0	0	72	0
MPI_Comm_size()	0	0	72	0
MPI_Recv()	142.179	142.179	792	0
aero_iso [{/home/inter	2.079	32.924	237,600	475,200
calcola_elementi [{/ho	0	0	72	0
chemnew [{/home/inte	0.375	160.998	237,600	237,600
copia_vettori_in [{/hon	3.888	3.888	792	0
datetm [{/home/intern	0.001	0.001	72	0
horizae [{/home/inter	7.755	82.626	144	73,584
MPI_Bcast()	16.155	16.155	432	0
MPI_Comm_rank()	0	0	144	0
MPI_Comm_size()	0	0	144	0
MPI_Recv()	15.138	15.138	4,752	0
blcuvs [{/home/inte	6.884	6.884	15,840	0
blcuvsae [{/home/i	21.517	21.517	15,840	0
copiax_caein [{/hor	9.146	9.146	792	0
copiax_cin [{/home,	2.754	2.754	792	0
copiay_caein [{/hor	2.422	2.422	1,584	0
copiay_cin [{/home,	0.758	0.758	1,584	0
diffvs [{/home/inter	0.099	0.099	31,680	0
iaddrs [{/home/interni,	0.001	0.001	864	0

Slave processes

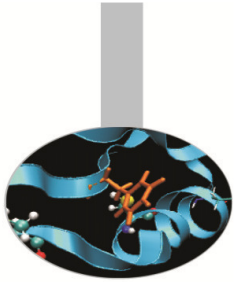
opspltae [{/home/interni/	5.961	460.322	72	1,036,220
MPI_Bcast()	21.115	21.115	648	0
MPI_Comm_rank()	0	0	72	0
MPI_Comm_size()	0	0	72	0
MPI_Send()	0.191	0.191	72	0
aero_iso [{/home/inte	3.243	41.528	380,160	760,320
chemnew [{/home/inte	0.606	268.726	380,160	380,160
copia_vettori_out [{/h	0.465	0.465	72	0
datetm [{/home/interr	0.001	0.001	72	0
horizae [{/home/inter	10.553	95.75	144	83,952
MPI_Bcast()	30.98	30.98	432	0
MPI_Comm_rank()	0	0	144	0
MPI_Comm_size()	0	0	144	0
MPI_Send()	21.505	21.505	432	0
blcuvs [{/home/int	7.722	7.722	20,592	0
blcuvsae [{/home/i	23.975	23.975	20,592	0
copiax_caeout [{/h	0.402	0.402	72	0
copiax_cout [{/hom	0.12	0.12	72	0
copiay_caeout [{/h	0.288	0.288	144	0
copiay_cout [{/hom	0.064	0.064	144	0
diffvs [{/home/inte	0.14	0.14	41,184	0
iaddrs [{/home/interni	0.001	0.001	864	0

Communication issues

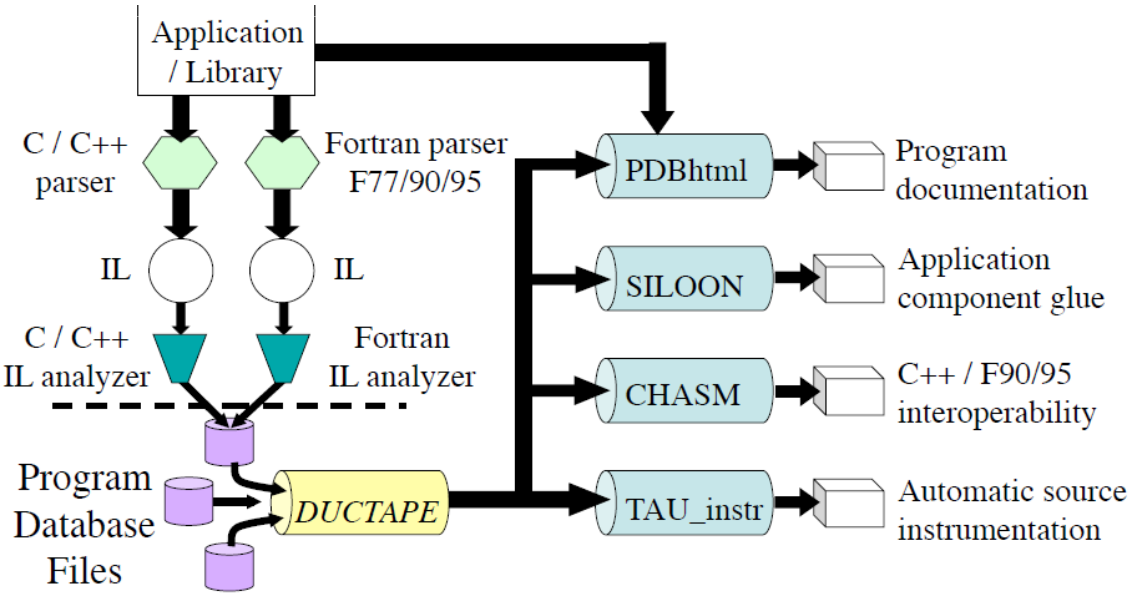
Load balancing issues

The imbalance of computational load causes an overhead in the MPI directives due to long synchronization times reducing the scalability

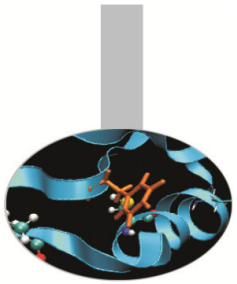
TAU source instrumentation with PDT



- TAU provides an API which can be useful when it's necessary to focus on particular sections of code to have more detailed information.
- Sometimes, for complex routines manual source instrumentation can become a long and error prone task.
- With TAU, instrumentation can be inserted in the source code using an automatic instrumentor tool based on the Program Database Toolkit (PDT).



TAU source instrumentation with PDT



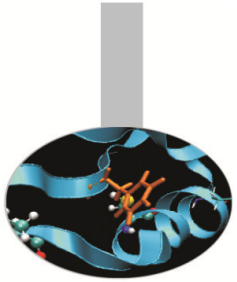
TAU and PDT howto:

- Parse the source code to produce the .pdb file:
  - `cxxparse file.cpp  C++`
  - `cparse  file.c  C`
  - `f95parse file.f90  Fortran`

- Instrument the program:
  - `tau_instrumentor file.pdb file.cpp -o file.inst.cpp -f select.tau`

- Complile:
  - `tau_compiler.sh file.inst.cpp -o file.exe`

TAU source instrumentation with PDT



- The "`-f`" flag associated to the command "`tau_instrumentator`" allows you to customize the instrumentation of a program by using a selective instrumentation file. This instrumentation file is used to manually control which parts of the application are profiled and how they are profiled.
- Selective instrumentation file can contain the following sections:

1. Routines exclusion/inclusion list:

```
BEGIN_EXCLUDE_LIST / END_EXCLUDE_LIST
BEGIN_INCLUDE_LIST / END_INCLUDE_LIST
```

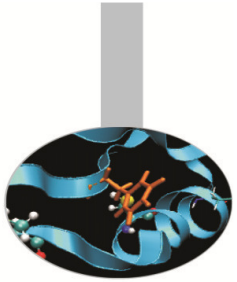
2. Files exclusion/inclusion list:

```
BEGIN_FILE_EXCLUDE_LIST / END_FILE_EXCLUDE_LIST
BEGIN_FILE_INCLUDE_LIST / END_FILE_INCLUDE_LIST
```

3. More detailed instrumentation specifics:

```
BEGIN_INSTRUMENT_SECTION / END_INSTRUMENT_SECTION
```

TAU source instrumentation with PDT



In a `BEGIN_INSTRUMENT_SECTION/END_INSTRUMENT_SECTION` block it's possible to specify the profiling of:

- Cycles

```
loops file="filename.cpp" routine="routinename"
```

- Memory

```
memory file="filename.f90" routine="routinename"
```

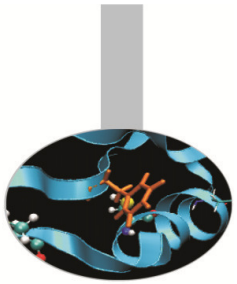
- I/O with dimension of read/write data

```
io file="foo.f90" routine="routinename"
```

- Static and dynamic timers

```
static/dynamic timer name="name" file="filename.c" line=17
   to line=23
```

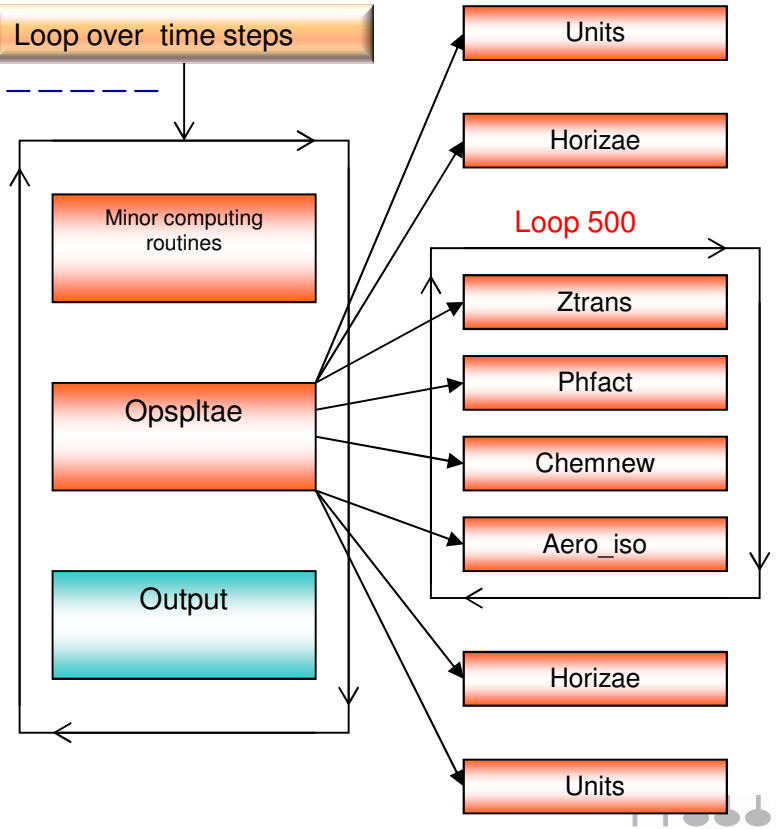
TAU with PDT Real Case Air Pollution Model



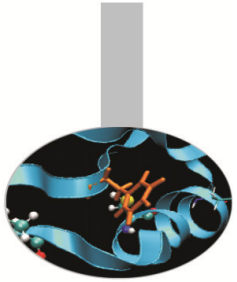
Custom profiling

Instrumentation file : instrument_rules.txt

```
-----------------------------------------
BEGIN_FILE_INCLUDE_LIST
opspltae.f
chemnew.f
horizae.f
ztrans.f
END_FILE_INCLUDE_LIST


BEGIN_INSTRUMENT_SECTION

loops file="opspltae.f" routine="OPSPLTAE"
loops file="chemnew.f" routine="CHEMNEW"
loops file="horizae.f" routine="HORIZAE"
loops file="ztrans.f" routine="ZTRANS"
io file="wrout1.f" routine="WROUT1"
dynamic timer name="dyn_timer" file="opspltae.f" line=183 to line=189
END_INSTRUMENT_SECTION
-----------------------------------------
```



TAU with PDT Real Case Air Pollution Model



Routine opspltae: Loop 500, TAU automatic instrumentation

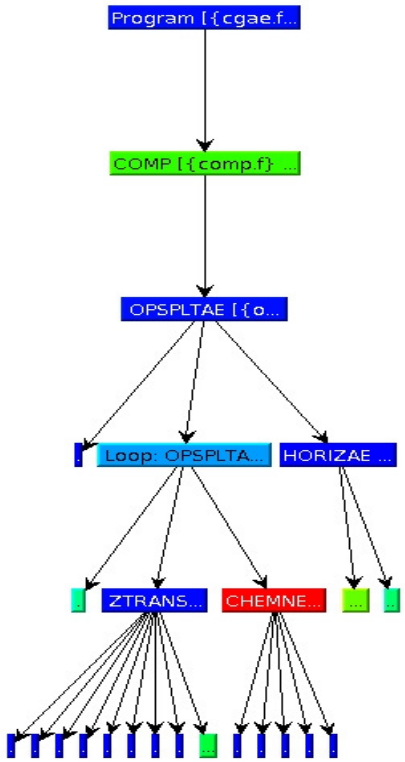
```
call TAU_PROFILE_TIMER(profiler, 'OPSPLTAE [{opspltae.f} {2,18}]')
call TAU_PROFILE_START(profiler)
call TAU_PROFILE_TIMER(t_131, ' Loop: OPSPLTAE [{opspltae.f} {131,7}-{143,12}]')
call TAU_PROFILE_TIMER(t_195, ' Loop: OPSPLTAE [{opspltae.f} {195,10}-{203,17}]')
call TAU_PROFILE_TIMER(t_247, ' Loop: OPSPLTAE [{opspltae.f} {247,7}-{592,14}]')
call TAU_PROFILE_TIMER(t_597, ' Loop: OPSPLTAE [{opspltae.f} {597,10}-{605,17}]')
call TAU_PROFILE_TIMER(t_639, ' Loop: OPSPLTAE [{opspltae.f} {639,10}-{647,17}]')
iugrid= iaddrs('UGRID   ',1,1,1,1,1)
                ……
 call TAU_PROFILE_START(t_247)
   do 500 i=2,nxm1
      do 500 j=2,nym1
      ……
      ……
   500   continue
call TAU_PROFILE_STOP(t_247)
```

TAU TIMER Initialization

TAU Loop 500 instrumentation

TAU Loop 500 end instrumentation

TAU with PDT Real Case Air Pollution Model



File Options Windows Help

Name △	Exclusive TIME	Inclusive TIME	Calls	Child Cal...
Program [{cgae.f} {111.7}]	0.652	1.913.031	1	2
COMP [{comp.f} {2.18}]	304.466	1.912.365	1	72
OPSPLTAE [{opspltae.f} {2.18}]	5.645	1.607.9	72	288
HORIZAE [{horizae.f} {2.18}]	0	219.192	72	144
Loop: OPSPLTAE [{opspltae.f} {131.7}-{143.12}]	0.185	0.185	72	0
Loop: OPSPLTAE [{opspltae.f} {247.7}-{592.14}]	63.181	1.165.318	72	10.445.760
AERO_ISO [{aero_iso.f} {2.18}]	171.098	171.098	4.419.360	0
CHEMNEW [{chemnew.f} {2.18}]	742.535	742.763	4.419.360	500.005
Loop: CHEMNEW [{chemnew.f} {64.7}-{66.14}]	0.033	0.033	100.001	0
Loop: CHEMNEW [{chemnew.f} {81.7}-{92.14}]	0.045	0.045	100.001	0
Loop: CHEMNEW [{chemnew.f} {103.7}-{106.14}]	0.025	0.025	100.001	0
Loop: CHEMNEW [{chemnew.f} {124.7}-{134.14}]	0.095	0.095	100.001	0
Loop: CHEMNEW [{chemnew.f} {145.7}-{148.14}]	0.029	0.029	100.001	0
ZTRANS [{ztrans.f} {2.18}]	2.333	188.276	1.607.040	2.407.048
Loop: ZTRANS [{ztrans.f} {101.7}-{104.14}]	0.038	0.038	100.001	0
Loop: ZTRANS [{ztrans.f} {108.7}-{114.14}]	0.031	0.031	100.001	0
Loop: ZTRANS [{ztrans.f} {131.7}-{134.14}]	0.028	0.028	100.001	0
Loop: ZTRANS [{ztrans.f} {137.7}-{145.14}]	0.034	0.034	100.001	0
Loop: ZTRANS [{ztrans.f} {156.7}-{160.14}]	0.028	0.028	100.001	0
Loop: ZTRANS [{ztrans.f} {203.7}-{206.14}]	0.026	0.026	100.001	0
Loop: ZTRANS [{ztrans.f} {209.7}-{222.14}]	0.027	0.027	100.001	0
Loop: ZTRANS [{ztrans.f} {236.7}-{247.14}]	0.04	0.04	100.001	0
Loop: ZTRANS [{ztrans.f} {253.7}-{351.14}]	185.692	185.692	1.607.040	0
dyn_timer [0]	0	2.467	1	1
dyn_timer [1]	0	3.262	1	1
dyn_timer [2]	0	3.255	1	1
dyn_timer [3]	0	3.209	1	1
dyn_timer [4]	0	3.215	1	1
dyn_timer [5]	0	3.21	1	1
dyn_timer [6]	0	3.224	1	1

Profiling time with default routine level compiler based instrumentation : 4192 sec

Profiling time with PDT and selective instrumentation : **1913 sec**

Execution time without profiling overhead: **1875 sec**